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An Analysis of Moisture Accumulation in the Roof Cavities of Manufactured Housing

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ABSTRACT: A detailed computer analysis is conducted to investigate whether moisture problems occur in the roof cavity of manufactured homes constructed in compliance with the current Department of Housing and Urban Development (HUD) Standards for manufactured housing. The current HUD Standards require a ceiling vapor retarder, but do not require outdoor ventilation of the roof cavity. In cold climates, the analysis revealed that moisture accumulates at lower roof surface and poses a risk of material degradation.

The analysis found the following combination of passive measures to be effective in preventing detrimental winter moisture accumulation at lower surface of the roof: 1) providing a ceiling vapor retarder, 2) sealing penetrations and openings in the ceiling construction, and 3) providing natural ventilation openings in the roof cavity.

In addition, the performance of a roof cavity exposed to a hot and humid climate is investigated. The analysis revealed that outdoor ventilation of the roof cavity causes the monthly mean relative humidity at the upper surface of the vapor retarder to exceed 80%. This condition is conducive to mold and mildew growth.

KEYWORDS: attic ventilation, HUD Manufactured Home Construction and Safety Standards, manufactured housing, mobile homes, moisture control guidelines, moisture in attics

Nomenclature

C	Specific heat, J/kg · °C
D_γ	Diffusivity for moisture gradient, m²/s
D_T	Diffusivity for temperature gradient, m²/°C · s
$f(\phi)$	Sorption isotherm function
k	Thermal conductivity of porous material, W/m · °C
P	Pressure, Pa
t	Time, s
T	Temperature, °C
y	Distance from inside surface of wall, m
α	Solar absorptance
γ	Moisture content on dry basis, kg/kg
μ	Water-vapor permeability, kg/s · m² · Pa
ρ	Density, kg/m³
ϕ	Relative humidity

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Subscripts

d = Dry property
g = Saturated state
T = Temperature gradient
v = Vapor property
w = Moist or water property
γ = Moisture content gradient

Introduction

During the winter, the occupant activities in manufactured housing release moisture to the indoor air. The airtightness of mobile homes tends to be considerably better than that of site-built homes. This causes the indoor absolute humidity to be considerably higher than that of the outdoor air. The vapor pressure difference across the ceiling construction causes moisture to be transferred into the roof cavity by diffusion. In addition, the ceiling construction usually contains air leakage sites associated with lighting fixtures and other elements. The stack effect causes moist indoor air to exfiltrate through the ceiling construction and accumulate at the roof sheathing.

The moisture content of roof sheathing has not been studied in manufactured housing. However, Harrje et al. measured the moisture content of roof sheathing of a conventional house in Princeton, NJ [*1*]. Harrje found that the north-sloping roof sheathing absorbed water vapor during winter periods and reached a high moisture content of 20% during midwinter. When the outdoor temperature rose in the spring, the moisture content of the roof sheathing dried out and decreased to a low value of 5%.

Relative to the above discussion, the maximum amount of moisture that can be stored in roof sheathing is denoted by "fiber saturation." Above fiber saturation, liquid water appears in the pore structure of the material. Fiber saturation is generally regarded as the maximum amount of moisture that can be taken on without degradation.

Higher roof sheathing moisture contents are likely to occur in manufactured houses compared to conventional houses. Manufactured houses tend to have higher indoor relative humidity compared to conventional houses because they have smaller volumes and lower rates of natural infiltration. In addition, the Department of Housing and Urban Development (HUD) Manufactured Home Construction and Safety Standards[2] do not currently require ventilation openings in the roof cavity [*2*]. As a result, many manufactured houses are constructed without ventilation openings.

A few field surveys documenting moisture problems in the roof cavity of manufactured housing are reported in the literature. For example, Zieman and Waldman conducted a field survey of 49 manufactured houses located in different parts of the United States which had unresolved moisture problems [*3*]. Twenty-nine percent of the houses surveyed had roof cavity condensation problems, evidenced by stains at the interior surface of ceiling boards. In addition, Lee [*4*] surveyed 65 manufactured houses in Alberta, Canada and reported that condensation was a problem in the roof cavity, although Canadian mobile homes are not required to be constructed in compliance with the HUD Standards.

Discussion of Model

A detailed computer model, called MOIST, has been developed at the National Institute of Standards and Technology (NIST) that predicts the moisture content and temperature

[2] For the sake of brevity, the HUD Manufactured Home Construction and Safety Standards will henceforth be referred to as the HUD Standards.

versus time for the construction layers of a building envelope [5]. The computer model is available from NIST.

Theory

Within each layer of a roof cavity, moisture transfer is governed by the following one-dimensional conservation of mass equation

$$\frac{\partial}{\partial y}\left(D_\gamma(\gamma, T)\frac{\partial \gamma}{\partial y}\right) + \frac{\partial}{\partial y}\left(D_T(\gamma, T)\frac{\partial T}{\partial y}\right) = \frac{\partial \gamma}{\partial t} \tag{1}$$

The selection of moisture content γ and temperature T as potentials has the advantage that the same mathematical formulation represents both diffusion transfer and capillary transfer. This formulation is equivalent to using water-vapor pressure as the moisture transfer potential in the diffusion regime and suction pressure in the capillary flow regime with a single required diffusivity.

Heat transfer is governed by the one-dimensional conservation of energy equation

$$\frac{\partial}{\partial y}\left(k(\gamma, T)\frac{\partial T}{\partial y}\right) = \rho(C_d + \gamma C_w)\frac{\partial T}{\partial t} \tag{2}$$

Latent transport of heat is included at the boundaries of the layers. The other components of enthalpy transport by moisture movement are generally small and are therefore neglected in the analysis. The term $(C_d + \gamma C_w)$ includes the effect of energy storage in both the dry material and accumulated moisture.

In the above two governing equations, strong couplings exist between heat and moisture transfer. Both the diffusivity for the moisture gradient D_γ and the diffusivity for the temperature gradient D_T are strong functions of moisture content and temperature. The thermal conductivity k can also be a function of moisture content and temperature, but for the present analysis it is assumed to be constant.

When the moisture content of a material is below fiber saturation, the diffusivity for the moisture gradient D_γ and the diffusivity for the temperature gradient D_T are calculated by the relations

$$D_\gamma = \frac{\mu(\phi)P_{vs}(T)}{\rho_d \dfrac{\partial f(\phi)}{\partial \phi}} \quad \text{and} \quad D_T = \frac{\mu(\phi)\phi \dfrac{\partial P_{vs}(T)}{\partial T}}{\rho_d} \tag{3}$$

The above equations may be derived by introducing the sorption isotherm function $f(\phi)$ and applying the chain rule to Fick's steady-state diffusion equation with the gradient of the water-vapor pressure as the driving-force potential.

When the moisture content of a material is above fiber saturation, a liquid diffusivity D_γ is used in Eq 1. It is calculated using procedures given in Burch and Thomas [5]. The diffusivity for the temperature gradient D_T is calculated using the second relation of Eq 3.

The model also has a provision for including nonstorage layers (e.g., an air space, glass-fiber insulation, a vapor retarder, etc.) that may be sandwiched between two storage layers. In a nonstorage layer, the storage of heat and moisture is neglected, and the transfer of heat and moisture is assumed to be steady state. A nonstorage layer may be convectively coupled to indoor and outdoor air.

Solution Procedure

Equations 1 and 2 were recast into finite-difference equations using a uniform nodal spacing within each layer. An implicit solution technique with coupling between the two conservation equations was used to solve the equations. A FORTRAN 77 computer program, called MOIST, with a tridiagonal-matrix solution algorithm was prepared. At each time step, the calculation proceeds by first solving for the temperature distribution, followed by a set of moisture contents. By choosing a sufficiently small time step (i.e., 1 h), there is no need to iterate between the temperature and moisture solutions.

Model MOIST was used to analyze the moisture accumulation in roof construction subjected to both a cold climate and a hot and humid climate. For the baseline roof construction (Fig. 1), two nodes were used for the gypsum board, sixteen in the roof sheathing, and two in the roofing paper and asphalt shingles. The kraft paper, glass fiber insulation, and the air space were combined into a single nonstorage layer. When the computer program was run on a Model 386 personal computer with a 33 MHz clock speed, equipped with a math coprocessor, about 60 min of computer time was required to simulate one year of real time.

Description of Baseline Roof Construction

The roof construction shown in Fig. 1 was analyzed. An insulation thermal resistance of $R - 2.5$ m$^2 \cdot$ K/W (14 h $\cdot$ ft$^2 \cdot$ °F/Btu) was used in the cold climate analysis and R $-$ 1.9 m$^2 \cdot$ K/W (11 h $\cdot$ ft$^2 \cdot$ °F/Btu) in the hot and humid climate analysis. Two roof sheathing materials were considered: 12 mm (15⁄32 in.) exterior-grade plywood and 11 mm (7⁄16 in.) oriented strand board (OSB). In addition, a metal roof consisting of a single layer of 0.33 mm (0.013 in.) galvanized steel was analyzed.

Since the mathematical model used for the analysis was one dimensional, it could not include the effect of wood-framing members. The moisture content of the roof sheathing of actual construction would tend to be a little lower than the theoretical predictions of the present report, due to the additional storage of moisture provided by wood-framing members.

Parameters Used in Analysis

The following diffusion properties and boundary conditions were used as input for the model MOIST.

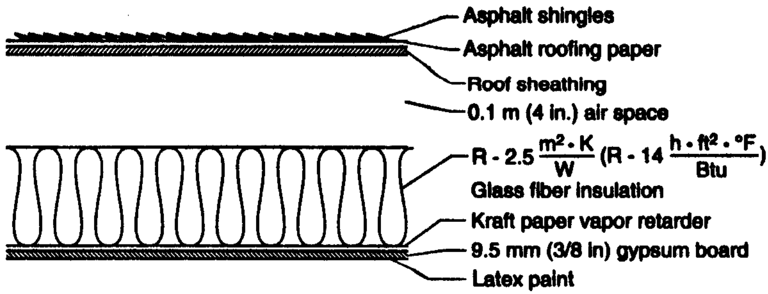


FIG. 1—*Roof construction.*

Parameters for Baseline Construction

Significant features of the baseline construction shown in Fig. 1 include a ceiling vapor retarder having a nominal permeance of 5.7×10^{-11} kg/Pa · s · m^2 (1 perm) and a roof solar absorptance of 0.7.

Ventilation Rate for Roof Cavity—For the baseline roof construction, it was assumed that the roof cavity had no ventilation openings. For this case, it was assumed that outdoor air infiltrated into the roof cavity through cracks in the construction at a rate of 0.25 air changes per hour (ach). Multiplying by the cavity volume and dividing by the ceiling area gives a volumetric infiltration rate per unit area of ceiling of 1.2×10^{-5} m^3/s per m^2 (0.14 ft^3/h per ft^2).

The following four cavity air exchange rates were analyzed:

Description	Air Exchange Rate m^3/s per m^2	(ft^3/h per ft^2)
Perfectly Sealed Cavity	0.0	(0.0)
Cavity without Ventilation Openings	1.2×10^{-5}	(0.14)
Cavity with Ventilation Openings	8.5×10^{-5}	(1.0)
Mechanically Ventilated Cavity	4.2×10^{-4}	(5.0)

A perfectly sealed attic is an idealization that is virtually impossible to achieve in practice. The air exchange rate for a cavity with ventilation openings and a mechanically ventilated cavity are based on assumed volumetric ventilation rates of 2 and 10 ach, respectively.

Indoor Air Exfiltration Rate into Roof Cavity—The ceiling of a manufactured house usually contains a light fixture in each room. During the winter, indoor air is warmer and therefore lighter than colder outdoor air. As a result, the stack effect on the indoor air causes indoor air to exfiltrate through air leakage sites around the light fixtures and other air leakage sites.

In selecting an exfiltration rate for the baseline roof construction, it was assumed that the total house infiltration rate was 0.25 ach. In addition, it was assumed that half was induced by temperature-difference (i.e., stack effect) driving force, while the remainder was induced by wind-speed driving force. This 50/50 percent breakdown is consistent with measurements reported by Goldschmidt and Wilhelm [6]. Furthermore, it was assumed that about one third of the stack effect portion exfiltrates into the roof cavity, while the other two thirds exfiltrate through the upper portion of the walls to the outdoor environment. This gives an exfiltration rate into the roof cavity of 0.042 ach. Multiplying by the house volume and dividing by its ceiling area gives a volumetric rate per unit ceiling area of 2.5×10^{-5} m^3/s per m^2 (0.30 ft^3/h per ft^2).

The following four rates of exfiltration are analyzed in the paper:

Description	Exfiltration Rate m^3/s per m^2	(ft^3/h per ft^2)
Perfectly Sealed Ceiling	0.0	(0.0)
Well Sealed Ceiling	1.3×10^{-5}	(0.15)
Typical Ceiling	2.5×10^{-5}	(0.30)
Leaky Ceiling	5.1×10^{-5}	(0.60)

A perfectly sealed ceiling is an idealization that is very difficult to achieve in practice. The typical ceiling corresponds to the baseline roof construction discussed above. It was assumed that the exfiltration rate for a well-sealed ceiling was one half that for the typical ceiling, while it was assumed that the value for a leaky ceiling was twice that of the typical ceiling.

Outdoor Boundary Conditions

The outdoor temperature, relative humidity, and solar radiation were based on weather year for energy calculations (WYEC) hourly weather data for each of the five locations [*7*].

Diffusion Properties

A plot of the equilibrium moisture content versus relative humidity (called a sorption isotherm) for the construction materials is given in Fig. 2*a*. The sorption isotherm data were measured at NIST by Richards et al. [*8*]. The water-vapor permeability of the materials were

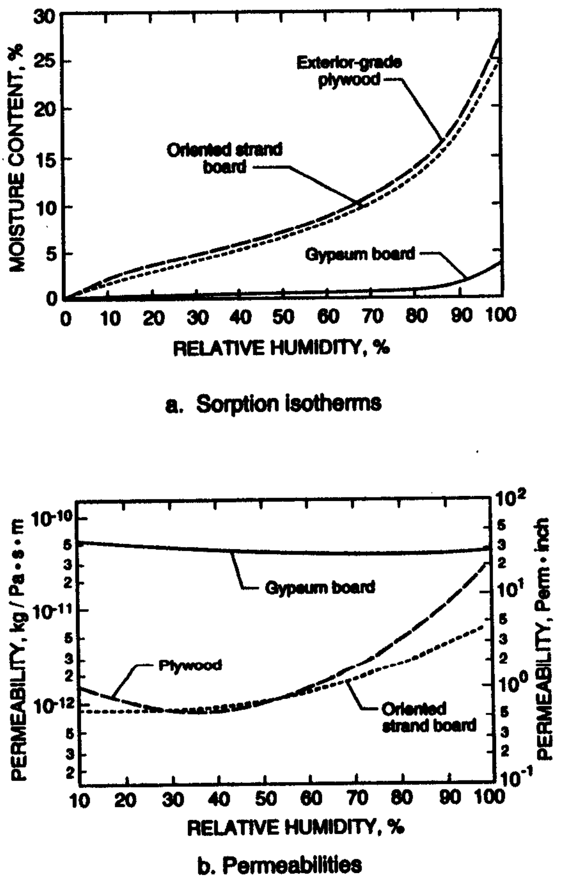


FIG. 2—*Diffusion properties of materials used in the analysis.*

also measured at NIST by Burch et al. [9]. Permeance is equal to the permeability of the material divided by its thickness. A plot of the permeance of the materials versus relative humidity is given in Fig. 2*b*.

In the analysis, latex paint, roofing paper and shingles, glass-fiber insulation, kraft paper, and the air space were treated as nonstorage layers. The permeance values for these materials are given in Table 1. In actual practice, the permeability of the roofing paper and shingles would have a very small finite value. However, treating these materials as impermeable has very little effect on the predicted moisture content of the roof sheathing. This is because the outflow of moisture from the roof sheathing to the outdoor environment is very small compared to the inflow of moisture from the air within the roof cavity, due to the small temperature difference between the roof sheathing and the outdoor environment and the low permeance of roofing paper and shingles.

Cold Climate Analysis

In the analysis, the indoor temperature and relative humidity are maintained at 21°C (70°F) and 50%, respectively, unless otherwise indicated. The use of an indoor relative humidity of 50% is warranted because manufactured homes are tighter and have lower infiltration rates and therefore tend to have higher indoor relative humidities than site-built homes. In fact, Zieman and Waldman report that manufactured homes have indoor relative humidities above 50% [3].

The outdoor temperature, relative humidity, and solar radiation are derived from weather year for energy calculations (WYEC) hourly weather data [7] for a mild winter heating climate (Atlanta, GA); and intermediate winter climate (Boston, MA); a cold winter climate (Madison, WI); and a Pacific northwest climate (Portland, OR). The heating degree days for these cities are 4228°C · days (7610°F · days) for Madison; 3207°C · days (5773°F · days) for Boston; 2579°C · days (4642°F · days) for Portland; and 1706°C · days (3071°F · days) for Atlanta. Figure 3 shows weekly average outdoor temperatures for these cities.

For each simulation, the performance of the roof cavity is predicted for a 1.5 year period. Six months of weather data are used to initialize the reported one-year simulations so that the initial moisture content and temperature would have a small effect on the results.

Results for Baseline Roof Construction

The moisture content of the plywood roof sheathing is plotted versus time of year in Fig. 4 for the climate of Madison, WI. During cold winter periods, indoor moisture is transferred into the roof cavity by way of diffusion and air exfiltration through the ceiling construction.

TABLE 1—*Permeance for nonstorage layers.*

Material	10^{-10} kg/s · m^2 · Pa
Latex Paint	5.7
Roofing Paper and Shingles	Impermeable
110 mm Glass Fiber Insulation	15
Kraft Paper (Asphalt Impregnated)	0.86
100 mm Air Space	17

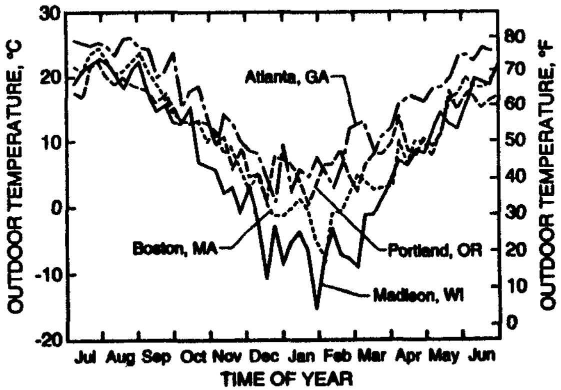


FIG. 3—*Weekly average outdoor temperature for the four winter climates.*

Moisture is adsorbed and accumulates at the plywood roof sheathing. During the spring, the elevated temperatures promote drying and the moisture content decreases.

The solid horizontal line depicts fiber saturation in the plywood roof sheathing. As previously mentioned, when the moisture content rises above fiber saturation, free liquid water exists within the pores of the material and a significant potential for material degradation exists. The moisture content of the plywood roof sheathing rises above fiber saturation for almost a three-month period. The plywood roof sheathing experiences repeated expansion and contraction cycles due to seasonal fluctuations in moisture content.

In subsequent sections, model MOIST is used to analyze the effect of various parameters on the performance of the baseline roof construction. Unless otherwise indicated, the roof sheathing is plywood and the climate is Madison, WI.

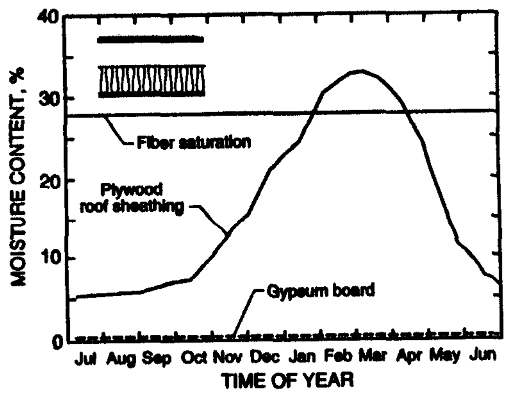


FIG. 4—*Moisture content of plywood roof sheathing plotted versus time of year for baseline roof construction located in Madison, WI.*

Effect of Significant Parameters

Outdoor Climate—The moisture content of the plywood roof sheathing is plotted versus the time of year in Fig. 5 for the four winter climates. Comparing the four curves, higher moisture contents occur in colder climates. In the two coldest climates (i.e., Madison and Boston), the moisture content rises above fiber saturation. These results indicate that climate is a very significant parameter affecting moisture accumulation in the roof sheathing of manufactured housing.

Comparing Figs. 3 and 5, the peak moisture content lags behind the minimum winter temperature by several months. This lag is due to moisture storage within the plywood roof sheathing.

It should be pointed out that the effect of climate may be less pronounced in actual manufactured houses because the indoor relative humidity does not remain constant and tends to decrease in colder climates as a result of increased moisture losses by window condensation and infiltration of drier outdoor air.

Indoor Air Exfiltration into Roof Cavity—Next, model MOIST is used to investigate the effect of indoor air exfiltration in the roof cavity. Results for four exfiltration rates are given in Fig. 6. The results show that air exfiltration into the roof cavity has a profound effect on the amount of moisture buildup. As the rate of air exfiltration increases, both the peak and breadth of the profiles increase. In addition, the peak moisture content for a well-sealed ceiling reaches fiber saturation for a brief period. These results illustrate the importance of sealing air leakage paths in the ceiling construction of manufactured housing.

Outdoor Ventilation of Roof Cavity—Next, model MOIST is used to investigate the effect of outdoor ventilation of a roof cavity with a ceiling vapor retarder. The moisture content of the plywood roof sheathing is plotted versus time of year for four outdoor ventilation rates in Fig. 7. These results reveal that providing natural ventilation significantly reduces both the peak and breadth of the profile. In fact, the peak moisture content is maintained slightly below fiber saturation. It will be shown later that natural ventilation, used in combination with sealing air leakage paths in the ceiling construction, maintains the peak moisture content considerably below fiber saturation. On the other hand, mechanical ventilation,

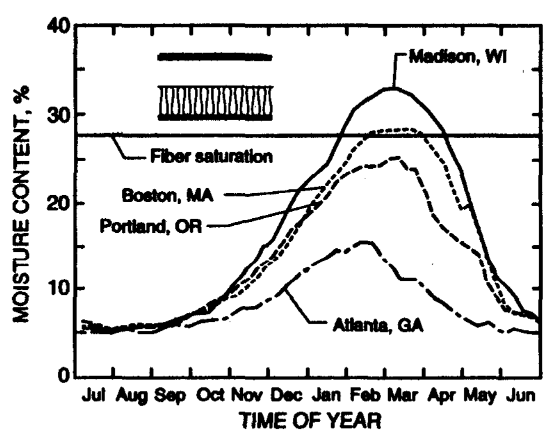


FIG. 5—*Moisture content of plywood roof sheathing plotted versus time of year for four winter climates.*

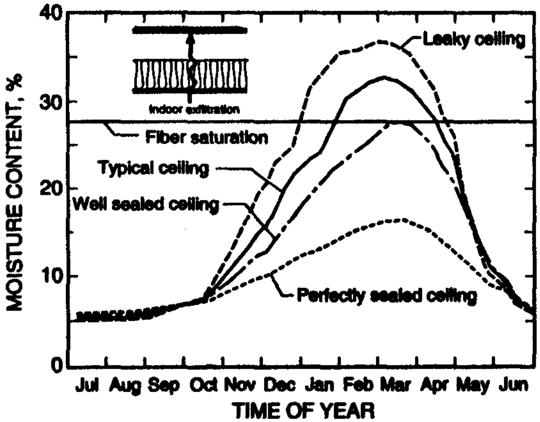


FIG. 6—*Moisture content of plywood roof sheathing plotted versus time of year for four exfiltration rates (Madison, WI).*

used in combination with a ceiling vapor retarder, reduces the peak moisture content well below fiber saturation.

Figure 8 shows similar simulation results for Portland. Here, it is seen that ventilation is still effective in reducing moisture accumulation in the roof sheathing. In this climate, the author was concerned that the outdoor air has higher relative humidity during the winter and therefore less drying capacity.

It should be pointed out that the above analysis assumes that providing outdoor ventilation for a roof cavity does not increase the exfiltration of indoor air into the roof cavity. TenWolde and Carll have recently shown that outdoor ventilation sometimes increase the exfiltration

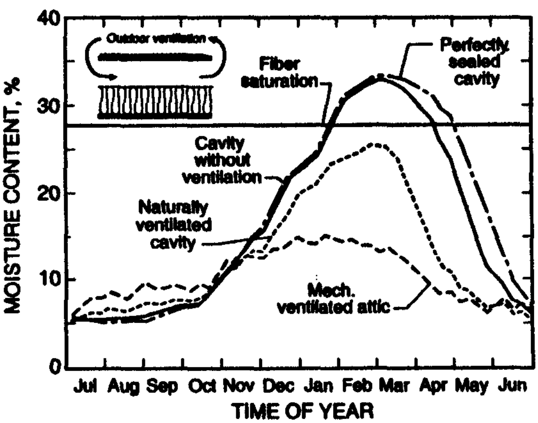


FIG. 7—*Moisture content of plywood roof sheathing plotted versus time of year for four roof cavity ventilation rates (Madison, WI).*

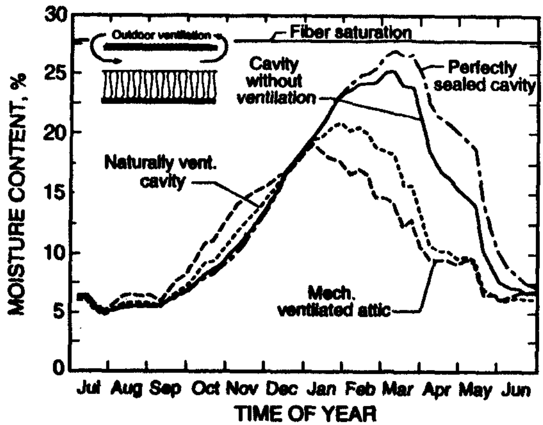


FIG. 8—*Moisture content of plywood roof sheathing plotted versus time of year for four roof cavity ventilation rates (Portland, OR).*

of indoor air into building cavities [*10*]. Since air exfiltration transports a considerable amount of moisture into building cavities, ventilation may in these instances be counterproductive, and a better strategy would be to improve the ceiling airtightness rather than to increase attic ventilation.

Indoor Relative Humidity—Separate computer runs were conducted for an indoor relative humidity of 35% and 50%. The results, given in Fig. 9, reveal that indoor relative humidity has an important effect on both the peak and breadth of the moisture content profile. For an indoor relative humidity of 35%, the peak moisture content is maintained below fiber saturation. On the other hand, for an indoor relative humidity of 50%, the moisture content is above fiber saturation for almost a three-month period.

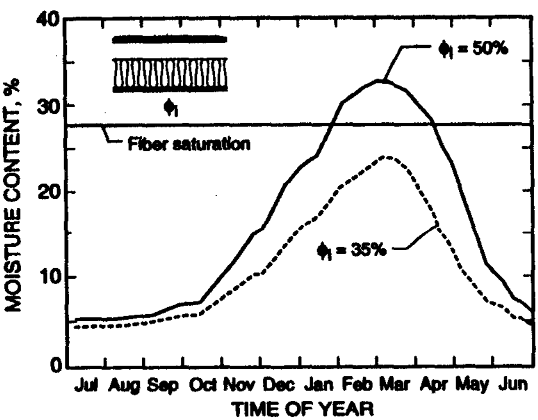


FIG. 9—*Moisture content of plywood roof sheathing plotted versus time of year for two indoor relative humidities (Madison, WI).*

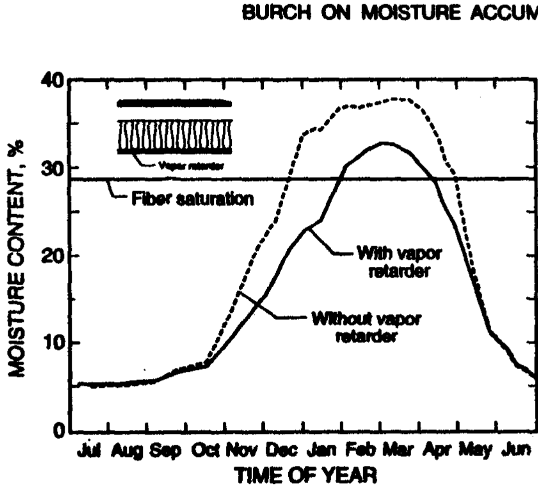


FIG. 10—*Moisture content of plywood roof sheathing plotted versus time of year for cases with and without a ceiling vapor retarder (Madison, WI).*

Ceiling Vapor Retarder—A computer simulation was conducted without a ceiling vapor retarder in the baseline roof construction. The results of this simulation are compared to the baseline construction with a vapor retarder in Fig. 10. As expected, the removal of the vapor retarder increases substantially both the peak and breadth of the profile. The HUD Standards currently require a ceiling vapor retarder. The results indicate this practice should continue.

Type of Roof Construction—Model MOIST was next used to analyze the moisture buildup for three roofing materials: exterior-grade plywood, oriented strand board (OSB), and galvanized steel roofing.

Figure 11*a* shows the results for plywood. The solid curve depicts the moisture content of a 2.4 mm (0.094 in.) thin surface layer, while the broken curve depicts the moisture content for the remaining bulk of sheathing. The moisture content of the thin surface layer is seen to follow closely that of the interior bulk layer, thereby indicating a small gradient in moisture content across the sheathing thickness.

Figure 11*b* shows similar results for OSB. This figure shows the thin surface layer has a considerably higher moisture content than the bulk layer during the winter. During this period, a significant gradient in moisture content exists across the thickness of the OSB sheathing, thereby providing a potential for buckling and warping.

The difference in behavior for the plywood and OSB sheathing was attributed to a difference in the permeability functions for the two materials. Figure 2*b* indicates that the permeability of plywood becomes large as the moisture content approaches fiber saturation. On the other hand, the permeability of OSB is considerably smaller. As a result, moisture at the surface of OSB is not readily transferred to its interior.

The moisture buildup at the lower surface of a galvanized steel roof is given in Fig. 11*c*. The horizontal line depicts an estimated amount of liquid water that the metal surface can retain without dripping off the surface.[3] Note that the peak moisture accumulation is about 2.1 kg/m^2 (0.43 lb/ft^2) which corresponds to about 2.1 mm (0.08 in.) water. If this moisture

[3] The maximum amount of retainable water was determined by spraying water onto the bottom surfaces of several pieces of galvanized steel roofing.

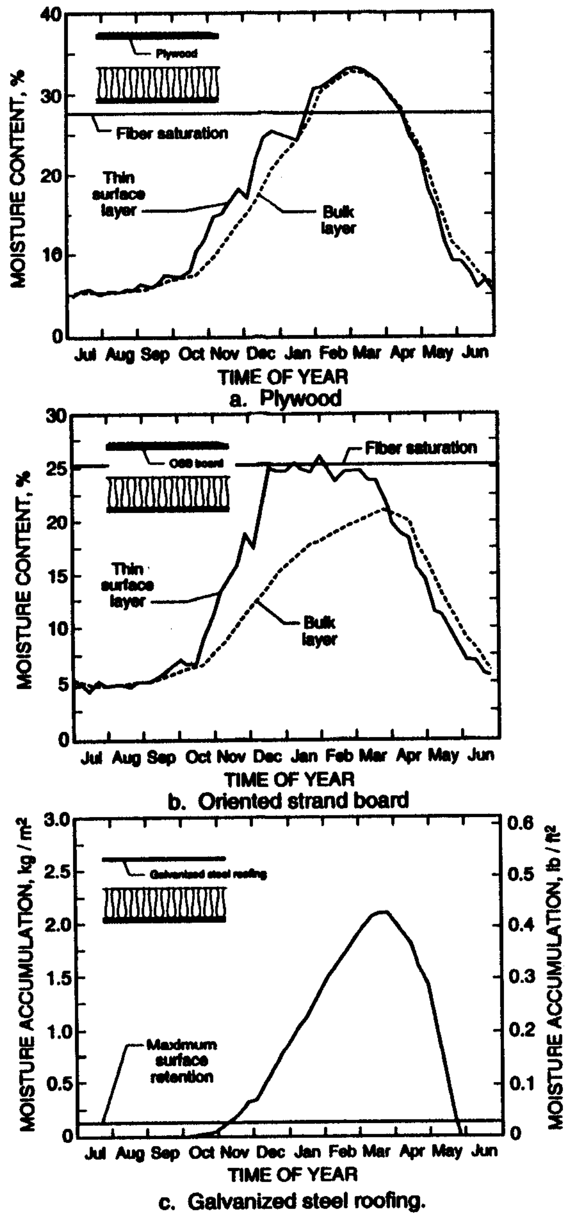


FIG. 11—*Moisture accumulation of roof plotted versus time of year for three roof constructions (Madison, WI).*

accumulates as frost and abruptly melts in the spring, it would drip through the fibrous insulation and puddle on the kraft paper. It is unlikely that the kraft paper could support this amount of puddled water. The gypsum board would then show stains where water leaked.

Effect of Other Parameters

Solar Absorptance of Roof—Three solar absorptances of the roof were analyzed: a light color ($\alpha = 0.3$), a typical medium-color ($\alpha = 0.7$), and a dark color ($\alpha = 0.9$). The results given in Fig. 12 indicate that lower moisture contents occur in darker roofs since they absorbed more solar radiation and dried more quickly.

Thermal Resistance of Ceiling Insulation—Two thermal resistance levels were analyzed: R – 2.5 $m^2 \cdot °C/W$ (14 $h \cdot ft^2 \cdot °F/Btu$) and R – 5.3 $m^2 \cdot °C/W$ (30 $h \cdot ft^2 \cdot °F/Btu$). The results given in Fig. 13 indicate that the addition of insulation has very little effect on roof moisture content.

Passive Moisture-Control Measures

The author followed the general approach of finding a combination of passive measures which would maintain the peak moisture content in hygroscopic roof sheathing and moisture accumulation at metal roofs below critical levels. The author gave preferential consideration to passive, as opposed to active, measures, because passive measures seem to be more likely to remain in effect during the life of the home. Passive measures also provide a lower first cost to the purchaser of the home.

For hygroscopic roof sheathing, a critical level was deemed to be fiber saturation. For metal roofs, we deemed a critical level to be a thickness of accumulated moisture (i.e., less than 0.8 mm or 1/32 in.) judged by the author to pose little or no condensation risk to the roof construction.

The following combination of passive measures was found to maintain the peak moisture content in the three roofs below critical levels:

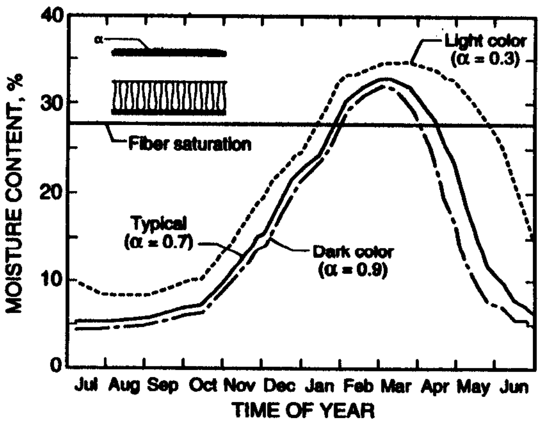


FIG. 12—*Moisture content of plywood roof sheathing plotted versus time of year for three solar absorptances (Madison, WI).*

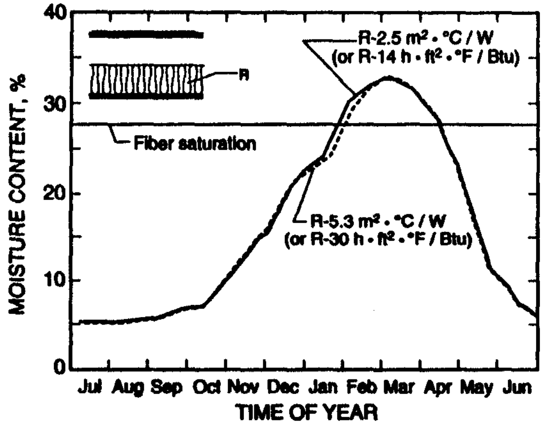


FIG. 13—*Moisture content of plywood roof sheathing plotted versus time of year for two insulation levels (Madison, WI).*

- a ceiling vapor retarder having a permeance less than 5.7×10^{-11} kg/Pa · s · m² (1 perm);
- sealing air leakage paths in the ceiling construction and attaining an exfiltration rate into the roof cavity less than 1.3×10^{-5} m³/s per m² (0.15 ft³/h per ft²);
- providing ventilation openings in the roof cavity and achieving a natural ventilation rate of 8.5×10^{-5} m³/s per m² (1.0 ft³/h per ft²).

The current HUD Standards require a ceiling vapor retarder, but do not require compliance with the other two recommended measures. The effectiveness of the recommended measures are analyzed below.

Plywood Roof Sheathing—Figure 14 shows the effectiveness of the three passive measures for plywood roof sheathing exposed to the four winter climates. In each plot, the upper curve is for a vapor retarder permeance of 5.7×10^{-11} kg/Pa · s · m² (1.0 perm), while the lower curve is for a vapor retarder permeance of 5.7×10^{-12} kg/Pa · s · m² (0.1 perm). A lower vapor retarder permeance was analyzed to investigate its merit.

In Fig. 14, the three passive measures are seen to maintain the peak moisture content considerably below fiber saturation. Since the three passive measures are very effective, it is unnecessary to obtain further reductions in the moisture content by decreasing the permeance of the vapor retarder.

Oriented Strand Board Roof Sheathing—Similar results for the OSB roof sheathing exposed to the climate of Madison are given in Fig. 15. Since moisture contents are highest in Madison, the results for only Madison are presented. These results indicate that the three passive measures maintain the peak moisture content below fiber saturation. Separate curves are given for a thin surface layer and a bulk interior layer, in order to illustrate that a gradient in moisture content still exists across the thickness of the OSB sheathing.

Galvanized Steel Roofing—Similar results are given in Fig. 16 for a galvanized steel roof exposed to the climate of Madison. The peak moisture accumulation is 0.41 kg/m² (0.082 lb/ft²) for a ceiling vapor retarder permeance of 5.7×10^{-11} kg/Pa · s · m² (1.0 perm). The fact that moisture accumulates above maximum surface retention for a three-month period means that the accumulated moisture will drip downwards onto the vapor retarder. However,

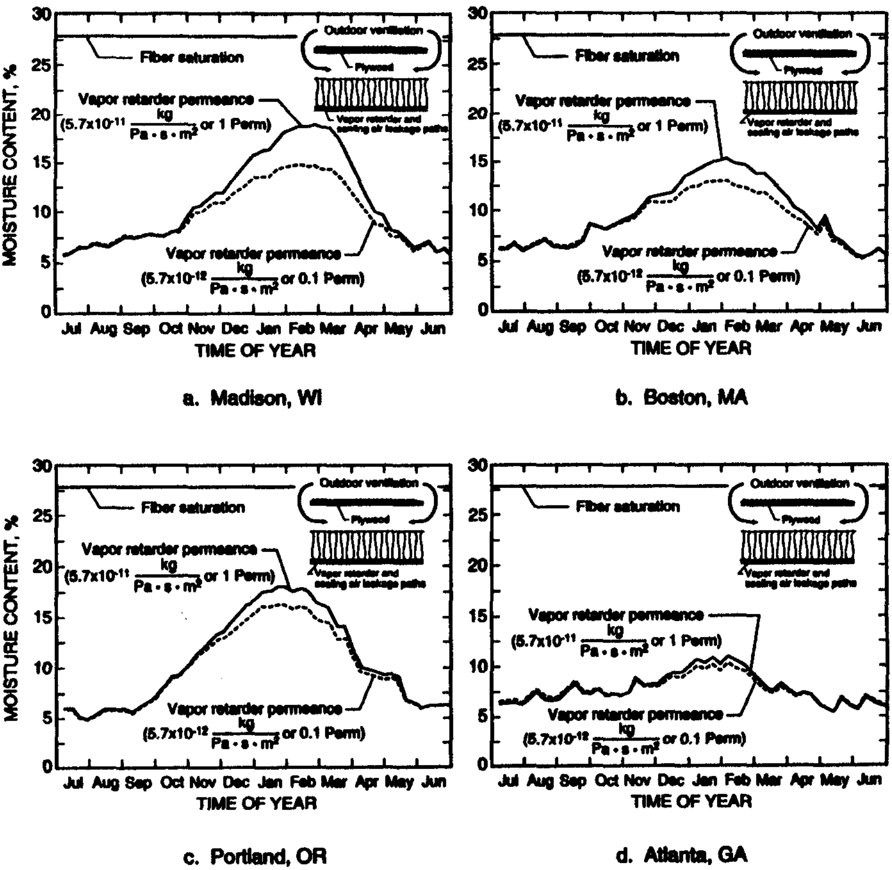


FIG. 14—*Effectiveness of recommended practices for plywood roof construction (i.e., sealing air leakage paths in the ceiling, naturally ventilating the roof cavity, and providing a ceiling vapor retarder).*

this amount of water corresponds to a thickness of 0.4 mm (1/64). It was believed that this amount of water poses little or no risk to the roof construction.

Hot and Humid Climate Analysis

Model MOIST was next used to predict the performance of the roof construction exposed to a hot and humid climate (i.e., Lake Charles, LA). In the analysis, the indoor temperature and relative humidity were 24°C (76°F) and 50%, respectively.

Unventilated Roof Construction

First, roof construction in compliance with the current HUD Standards was considered. The construction given in Fig. 1 was used. A kraft-paper vapor retarder is installed in the ceiling, but openings are not provided to naturally ventilate the roof cavity.

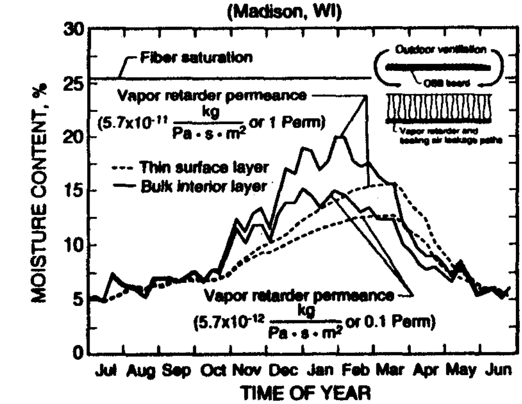


FIG. 15—*Effectiveness of recommended practices for OSB roof construction (i.e., sealing air leakage paths in the ceiling, naturally ventilating the roof cavity, and providing a ceiling vapor retarder).*

The weekly-average relative humidity at the upper and lower surfaces of the kraft-paper are plotted versus time of year in Fig. 17*a*. At the upper surface, the relative humidity rises and reaches a peak during the summer. On the other hand, the relative humidity at the lower surface departs very little from the indoor value of 50%.

The solid horizontal line in Fig. 17*a* depicts a critical 80% level believed to coincide with the "onset for mold and mildew growth." The International Energy Agency has recently published Guidelines and Practices (Volume 2) for preventing mold and mildew growth at building surfaces [*11*]. This consensus document indicates that a monthly-mean surface relative humidity above 80% is conducive to mold and mildew growth. Note that the peak relative humidity at the upper surface of the kraft paper is below the critical 80% level. Therefore, mold and mildew growth is unlikely to occur in an unventilated roof cavity.

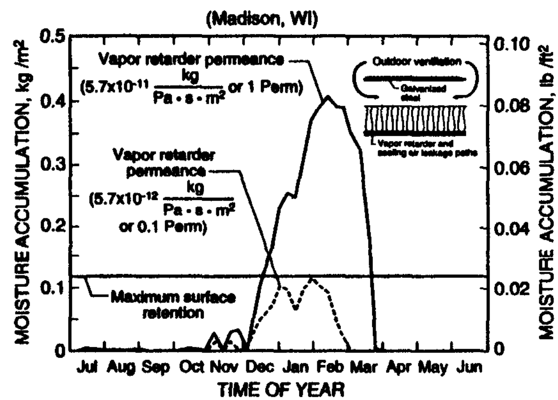
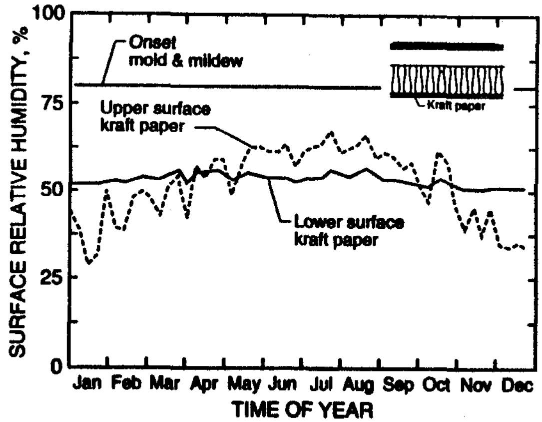
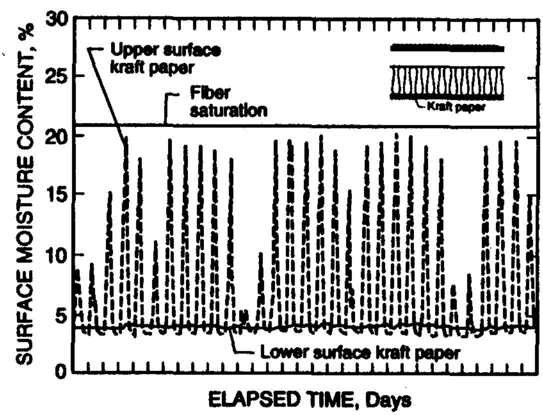


FIG. 16—*Effectiveness of recommended practices for galvanized steel roof construction (i.e., sealing air leakage paths in the ceiling, naturally ventilating the roof cavity, and providing a ceiling vapor retarder).*



a. Weekly average surface relative humidity



b. Hourly surface moisture content for July

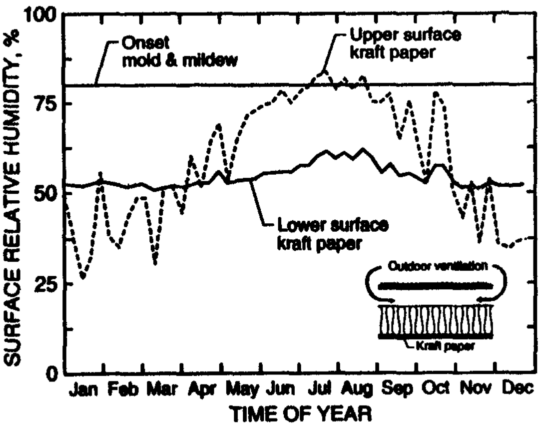
FIG. 17—*Moisture content of kraft paper plotted versus time for baseline construction exposed to hot and humid climate (unvented roof cavity).*

The hourly moisture content at the upper and lower surfaces of the kraft paper is plotted versus time for the month of July in Fig. 17*b*. At the upper surface, the moisture content undergoes large diurnal fluctuations. During warm day periods, moisture is transferred downwards and accumulates at the upper surface of the kraft paper which is cooled by indoor air conditioning. However, the moisture content never reaches fiber saturation (21%), indicating that liquid water is never present. TenWolde and Mei experimentally observed similar diurnal humidity fluctuations in walls [*12*].

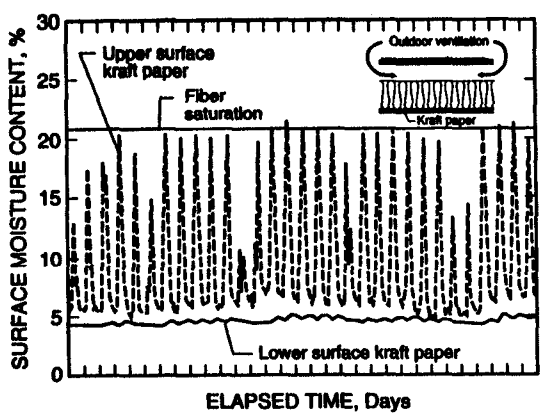
Ventilated Roof Cavity

Next, model MOIST was used to develop a similar pair of plots for a roof cavity ventilated at 2 ach. The results are given in Fig. 18.

The weekly-average relative humidity at the upper surface of the kraft paper rises above the critical 80% level for a two-month summer period (Fig. 18*a*). The moisture content at the upper surface sometime reaches fiber saturation (Fig. 18*b*). Such an environment is conducive to mold and mildew growth. It is possible that the operation of fans that ventilate the interior will cause air from the roof cavity to infiltrate and transport fungal spores to the indoors. This could result in an indoor air quality problem (i.e., musty odor).



a. Weekly average surface relative humidity



b. Hourly surface moisture content for July

FIG. 18—*Moisture content of kraft paper plotted versus time for baseline construction exposed to hot and humid climate (ventilated roof cavity).*

Based on the above results, the author recommends that roof cavities of manufactured housing *not* be ventilated in hot and humid climates.

Needs for Future Research

The author recommends that the findings of this theoretical study be corroborated by a comprehensive experimental study prior to implementation of rule changes for the HUD Standards for manufactured housing. Important aspects of this research would be to (1) measure the seasonal variation in moisture content of the roof sheathing in two side-by-side manufactured houses: one, a current practice house; the other, an identical house with the recommended moisture-control measures implemented, (2) measure outdoor air exchange rates for a roof cavity under a range of outdoor temperature and wind speeds and establish a relationship between the net free ventilation opening and the corresponding air exchange rate, and (3) measure the indoor air exfiltration rate into the roof cavity.

Summary and Conclusions

A detailed computer analysis was conducted of the combined transfer of heat and moisture in the roof construction of manufactured housing using hourly weather data for four winter climates: a cold winter climate (Madison, WI), an intermediate winter climate (Boston, MA), a mild winter climate (Atlanta, GA), and a Pacific northwest climate (Portland, OR).

The current HUD Standards for manufactured housing require that a ceiling vapor retarder be installed, but they do not require that the roof cavity be ventilated with outdoor air. In homes constructed to this standard, the computer predictions revealed that a detrimental amount of moisture accumulated at the roof sheathing of homes located in cold winter and intermediate winter climates. In plywood and oriented strand board roof sheathing, the peak moisture content during the winter rose above fiber saturation, indicating the presence of free liquid water in the pore structure of the materials. In this situation, degradation of the roof sheathing may occur. In metal roofs, a significant amount of moisture accumulated at the underside of the roof surface, which may drip downward wetting and staining the ceiling construction.

A sensitivity analysis was conducted to determine the effect of various parameters on roof moisture accumulation in cold climates. Parameters having a significant effect on the moisture accumulation in the roof sheathing included coldness of the climate, the airtightness and permeability of the ceiling construction, the outdoor ventilation rate of the roof cavity, indoor relative humidity, and roof type. Factors having a less important effect were the thermal resistance of the ceiling insulation and the solar absorptance of the roof.

The analysis revealed that the following combination of passive practices will prevent detrimental winter moisture accumulation at the roof sheathing of manufactured housing:

1. providing a ceiling vapor retarder having a permeance of 5.7×10^{-11} kg/Pa · s · m^2 (1 perm) or less,
2. sealing penetrations and openings in the ceiling construction, and
3. providing natural ventilation openings in the roof cavity.

Computer simulations were also carried out to investigate the performance of a roof cavity exposed to a hot and humid climate using weather data for Lake Charles, LA. In an unventilated attic, the accumulation of outdoor moisture at a ceiling vapor retarder, cooled by indoor air conditioning, was not a problem. However, when the roof cavity was naturally ventilated, intermittent wetting of the vapor retarder occurred during warm day periods. In this situation, the monthly mean relative humidity at the upper surface of the vapor retarder rose above 80% during the summer, thereby posing a risk for mold and mildew growth. For this reason, the author recommends that the roof cavities of manufactured homes not be ventilated in hot and humid climates.

It is recommended that a comprehensive experimental study be conducted to corroborate the theoretical findings of the present study.

Acknowledgments

The author would like to thank William Freeborne of the Division of Innovative Technology of the U.S. Department of Housing and Urban Development for funding this project and making many helpful suggestions during the review of the report. The author would also like to thank Felix Castillo of the National Conference of States on Building Codes and Standards, Inc. for providing information on the construction of manufactured housing.

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Discussions

Stephen N. Flanders[1] *(written discussion)*—You advocate three measures for cold climates. One of them, roof ventilation, is counterproductive in warm climates. What happens when one provides a vapor retarder, seals leaks, but omits ventilation in cold conditions?

[1] USA CRREL, Hanover, NH 03755.

D. Burch (author's closure)—In response to this question, the author used MOIST to investigate the effectiveness of an alternate set of practices which included installing a ceiling vapor retarder, providing supplemental ventilation of the indoors to comply with the ASHRAE Ventilation Standard 62 (i.e., 0.35 ach), and sealing air leakage sites in the ceiling construction. Here the roof cavity was assumed not to be ventilated, and the roof sheathing was plywood. The climate of Madison, WI was used as a worst-case cold climate.

The simulation results revealed that the alternate set of practices maintained the peak moisture content of the plywood roof sheathing considerably below fiber saturation, thereby posing little or no risk of material degradation. In particular, ventilating the indoors to comply with the ASHRAE Ventilation Standard 62 reduced the relative humidity of the indoor space, making it unnecessary to ventilate the roof cavity.

Anton TenWolde[2] *(written discussion)*—What was the orientation of the roof in your analysis?

Author's closure—The roof was treated as a horizontal surface.

G. Proskiw[3] *(written discussion)*—Does your model assume uniform air exfiltration across the ceiling or does it assume point or linear air exfiltration?

Author's closure—Air exfiltration across the ceiling was modeled as a constant flow rate of indoor air to a finite-difference node at the lower surface of the roof sheathing.

[2] Forest Products Laboratory, Madison, WI, 53705-2398.
[3] Proskiw Engineering Ltd., Winnipeg, Manitoba, Ontario, Canada.